N94-16354

THE SEISMIC RESPONSE OF AN AQUIFER TO THE PROPAGATION OF AN IMPACT GENERATED SHOCK WAVE: A POSSIBLE TRIGGER OF THE MARTIAN OUTFLOW CHANNELS?

Ivett A. Leyva[1] and Stephen M. Clifford[2]. [1]California Institute of Technology, Pasadena, California. [2]Lunar and Planetary Institute, Houston, Texas.

Aquifer dilation from shock waves produced by the 8.4 magnitude Alaskan earthquake of 1964 led to water and sediment ejection from the ground up to 400 km away from the earthquake's epicenter [1]. Groundwater disturbances were observed as far away as Perry, Florida (~5500 km), where well water fluctuations with an amplitude of as much as 2.3 m were reported [2]. The martian cratering record provides evidence that the planet has experienced numerous seismic events of a similar, and often much greater, magnitude. Given this fact, and the photogeologic evidence for abundant water in the early crust, we have investigated the response of a basalt aquifer to the propagation of compressional waves (P-waves) produced by impacts in the 33 - 1000 km diameter size range. The resulting one-dimensional changes in effective stress and pore pressure were calculated -- as a function of both distance and time -- based on the following assumptions: (i) that all of the seismic energy radiated by an impact is transmitted as a single compressional wave, (ii) that both the host rock and groundwater are compressible, and (iii) that there is no net flow between the water-filled pores.

After *Croft* [3], an impact producing a crater of final diameter D_f, has a corresponding maximum transient diameter D_{tc}, given by

$$D_{tc} = D_c^{0.15+0.04} D_f^{0.85+0.04} \qquad (1)$$

where D_c is the transition diameter between simple and complex crater morphology, which occurs on Mars at a crater diameter of ~ 6 km. According to *Grieve and Cintala* [4], the relation between the kinetic energy of the impactor and D_{tc} is given by

$$E_k = \frac{D_{tc}^{3.85}}{2.91\text{x}10^{-3}\, U^{-0.35}\, g^{-0.85}} \qquad (2)$$

where U is the velocity of the impactor, taken as 10 km s^{-1}, and g is the acceleration of gravity. However, upon impact, only a small fraction of E_k is actually converted into seismic energy, E_s. After *Schultz and Gault* [5,6]

$$E_s = k\, E_k \qquad (3)$$

where the seismic efficiency factor, k, is taken to be equal to 10^{-4}.

In this analysis, the propagation of the resultant seismic wave is represented by a sine wave with a period $\tau = 4{*}t_o$, where t_o is the time of formation which, after *Schmidt and Housen* [7], is given by

$$t_o = 0.62\, E_k^{0.13}\, U^{-0.04}\, g^{-0.61}\,. \qquad (4)$$

This quantity represents the elapsed time from impact until the wavefront reaches the maximum radius of the transient cavity, r_o (= $D_{tc}/2$) . The maximum stress of the P-wave occurs at r_o and is equal to

$$\sigma_o^2 = \frac{3\rho\, c\, E_s}{\pi\, r_o^2\, t_o} \qquad (5)$$

where ρ is the density of the martian crust and c is the velocity of the P-wave given by

$$c = \left(\frac{E}{\rho}\right)^{1/2}, \qquad (6)$$

where E is the Young's modulus (= $\lambda + 2\mu$, where λ and μ are the Lame parameters) [5]. After *Schultz and Gault* [6], the maximum stress associated with the outward propagating shock wave is given by

$$\sigma = \frac{\sigma_o r_o}{x}. \qquad (7)$$

The displacement of a particle at this distance, is assumed to oscillate according to the equation

$$u = A_o \sin(k x - \omega t) \qquad (8)$$

where ω is the angular frequency (= $2\pi/\tau$), k is the wave number (= ω/c), and where, after *Jaeger and Cook* [8], A_o is the maximum amplitude given by

$$A_o = \frac{\sigma c \tau}{2\pi E} \tag{9}$$

The change in strain, $d\varepsilon$, is then calculated from the derivative of eq. (8), such that

$$d\varepsilon = A_o k \cos(kx - \omega t) \tag{10}$$

After *Pande et al.* [9], the change in pore pressure, dp, is related to the change in strain, $d\varepsilon$, and change in effective stress, $d\sigma'$, by

$$dp = K_f \left(d\varepsilon - \frac{d\sigma'}{K_s} \right) \tag{11}$$

where

$$K_f = \left(\frac{n}{K_w} + \frac{1-n}{K_s} \right)^{-1} \tag{12}$$

and where n is the porosity of the material, K_s is the bulk modulus of the solid matrix, and K_w is the bulk modulus of the water saturating the pores.

The change in strain is related to the changes in total and effective stress ($d\sigma$ and $d\sigma'$ respectively) through the modulus matrix D^* and drained modulus matrix D [9], where

$$d\sigma = D^* d\varepsilon \tag{13}$$

$$d\sigma' = D\, d\varepsilon \tag{14}$$

and where D^* and D are related to each other by

$$D^* = D + K_f - \frac{K_f D}{3 K_s} \tag{15}$$

For the one-dimension case, D^* reduces to E and D can be solved from eq. (15). Substituting these values in eq. (11), the final equation for the change in pore pressure is found to be

$$dp = d\varepsilon\ K_f \left(1 - \frac{E - K_f}{3 K_s + K_f} \right) \tag{16}$$

To place the calculated pore pressure changes in perspective, note that during the Alaskan earthquake of 1964, changes on the order of 1.7 bars were produced in silt and clay sediments at distances up to 400 km away from the earthquake's epicenter (the maximum distance at which water and sediment ejections were observed). On Mars, an impact of equivalent seismic energy (D_f = 33 km [10]) will produce this same change in pressure in basalt at a distance of ~ 100 km, while impacts with diameters >500 km will produce pressure changes in excess of 1.7 bars on a global scale. Impacts with final diameters > 1000 km are capable of generating pore pressures in excess of 10 bars out to distances of over 2000 km. Given a more realistic representation of seismic wave propagation through a planetary body, these pore pressures changes are likely to be amplified enormously as the seismic waves converge at the antipode. These results suggest that seismic disturbances produced by large impacts may have played a role in triggering the martian outflow channels. For example, under conditions where the local hydraulic head in a confined aquifer is already near lithostatic levels, the excess pressure generated by a major impact could conceivably disrupt a several km-thick layer of frozen ground over global distances -- permitting the catastrophic discharge of the accumulated reservoir of groundwater until the local hydraulic head declined to the level of the surrounding topography. Efforts to extend this analysis to include a more realistic representation of seismic wave production and propagation, and to consider the effects of flow in a heterogeneous aquifer possessing both intergranular and fracture porosity, are currently underway.

References: [1] Waller, R.M. (1968). in: The Great Alaska Earthquake of 1964, National Academy of Sciences, 97-116. [2] Cooper, H.H., J.D. Bredehoeft, I.S. Papadopulos, and R.R. Bennet (1968). in: The Great Alaska Earthquake of 1964, National Academy of Sciences, 122-132. [3] Croft, S. K., (1985). *J. Geophys. Res.*, C828-C842. [4] Grieve, R.A.F., and M.J. Cintala. (1992). *Meteoritics*, *27, in press*. [5] Schultz, P.H., and D.E. Gault. (1975a). *The Moon*, **12**, 159-177. [6] Schultz, P.H., and D.E. Gault. (1975b). *Proc. Lunar Sci. Conf. 6th.*, 2845-2862. [7] Schmidt, R.M., K.R. Housen (1987). *Int. J. Impact Engng*. **5**, 543-560. [8] Jaeger, C., and G.W. Cook (1976). Fundamentals of Rocks Mechanics, Hapman and Hall., 352-254. [9] Pande, G.N., G. Bear, J.R. Williams. (1990). Numerical methods in rock mechanics. John Wiley & Sons Ltd., 143-145. [10] Clifford, S. (1992). *J. Geophys. Res.*, *in press*.